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Results are presented of studies of the space distribution and other properties of two significant classes of compact astrophysical sources which are bright at mid-infrared wavelengths: stars with excess infrared emission due to heated dust, and galaxies with nuclei that heat surrounding dust to anomalously high temperatures. The stellar studies reveal a complex structure for the galactic disk, which must be taken into account in the development of realistic infrared sky models. The extragalactic studies have been temporarily stalled by the remarkable discovery of low-luminosity stars with strong far-infrared spectral energy distributions mimicking warm galaxies! Much further observational work is needed to understand the origin of this emission.

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Observational Study and Analysis of Point Sources Found by the Infrared Astronomy Satellite

supported under AFOSR 88-0070

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SUMMARY: Results are presented of studies of the space distribution and other properties of two significant classes of compact astrophysical sources which are bright at mid-infrared wavelengths: stars with excess infrared emission due to heated dust, and galaxies with nuclei that heat surrounding dust to anomalously high temperatures. The stellar studies reveal a complex structure for the galactic disk, which must be taken into account in the development of realistic infrared sky models. The extragalactic studies have been temporarily stalled by the remarkable discovery of low-luminosity stars with strong far-infrared spectral energy distributions mimicking warm galaxies! Much further observational work is needed to understand the origin of this emission.

Statement of Work: The program described here is designed to analyze contents of the *IRAS* Sky Survey, in order to learn what classes of celestial objects it contains, and the three-dimensional space distribution of each of those classes. The technical goal of this work is to enable one to predict the number of sources that should be found in infrared sky surveys made at deeper levels of sensitivity, and at different infrared wavelengths than those employed for the *IRAS* Sky Survey. The scientific goals are to learn the rate of evolution and the rates of mass loss of various stellar types, refine our knowledge of the structure of the galactic disk, seek new classes of stars, learn the rate of evolution of infrared-bright galaxies, and understand the physical characteristics of infrared bright galactic nuclei. In the process of executing these studies, discoveries of new phenomena have added to the list of questions envisioned at the beginning of this project.

I. Significant Accomplishments

a) Stars

We have carried out a systematic program to deduce the space distribution of the largest classes of cool, luminous stars. Such stars are particularly well suited for determining the large-scale structure of the Milky Way, because

- they are old, and their locations trace out the mass of the galaxy rather than the locations of their births.
- they are common, since they are descendants of relatively low-mass stars, and therefore can provide a good statistical basis for deducing the mass distribution in the galaxy.
- they are extremely luminous, and can therefore be seen even at large distances. Further, their luminosity emerges in the infrared, where the interstellar medium is relatively transmissive.

The studies we have carried out emphasize the use of infrared all-sky surveys, since these surveys provide an objective basis for analyzing the space distributions of cool stars. In particular, we have used the *Two Micron Sky Survey* (Neugebauer and Leighton 1969) and the *IRAS Point Source Catalog* (1985). Important additional information came from efforts to obtain spectral classifications of sources in these catalogs, especially by Bidelman (1980). These spectral classifications are essential in order to distinguish different classes of cool stars. Finally, we have also used the *General Catalog of Variable Stars* (Kholopov *et al.* 1985-87), to differentiate cool stars with different types of temporal behavior.

To derive the distances to stars in various classes, we have used the results of studies of stars in the Large and Small Magellanic Clouds. These studies have shown that, for many of the types of variable stars in our samples, there is a relationship between the period of variability and the intrinsic luminosity in the near-infrared, similar to the optical period-luminosity relationship of Cepheids discovered nearly a century ago. Thus, comparison of the observed near-infrared brightness with the expected brightness (based on the observed period) gives a measure of the distance to a star. In some cases, other means of estimating distances were more appropriate, and these are summarized in the papers listed below.

Given the distances to each star in a sample of stars which could be shown to be statistically complete above a certain flux limit, we derived the local space density, and certain parameters of the space distribution. In particular, we assumed in all cases that the stars were distributed in a disk with an exponential scale height and an exponential scale length:

$$n = n_0 \exp(-|Z|/Z_0) \exp(-(R - R_*)/R_0)$$

where n_0 is the space density of stars of a given class in the galactic plane near the Sun, Z is the distance measured from the Galactic plane, Z_0 is an exponential scale height, R is the Galactocentric radius where the value for the sun is R_* and the scale length is R_0.

Using σ_0 to denote the surface density then

$$\sigma_0 = 2 n_0 Z_0$$

Table 1 below summarizes the results of studies done to date. They highlight the dramatic differences between the space distributions of

a. the supergiant stars (which all have oxygen-rich atmospheres; i.e., $O/C > 1$). These are the most massive of the evolved stars, having descended from main sequence stars with masses above 10 $M_\odot$, and still lie close to the galactic plane where they formed.

b. the cool stars whose atmospheres are richer in carbon than in oxygen (the carbon stars; $O/C < 1$) or whose atmospheres contain roughly as much oxygen as carbon (the S-type stars; $O/C \sim 1$). These stars are thought to be descendants of intermediate mass stars, i.e., those with $1 < M/M_\odot <$ 5-8. They therefore had longer hydrogen-burning lifetimes than the supergiants, and have therefore been scattered further from the plane than the supergiants.

c. various classes of cool stars whose atmospheres are richer in oxygen than carbon (M-type giants; $O/C > 1$. These stars are thought to be descendants of low-mass stars ($\sim$ 1 $M_\odot$). They therefore had even longer hydrogen-burning lifetimes than the carbon and S-type stars, and are scattered further from the galactic plane than those stars.

Though we modeled the distribution of all of these classes of stars in terms of a disk with both an exponential scale height and an exponential scale length, we found little concentration of any of the stars in our sample toward the galactic center. The supergiants, which can be detected out to very large distances with the surveys we used, appear not to be strongly concentrated toward the galactic center. A study of carbon stars in the galactic anti-center region (Jura, Joyce, and Kleinmann 1989) showed that they, too, show no strong concentration toward the galactic center. Finally, the oxygen-rich giants could not be seen to distances larger than their expected scale lengths, given the sensitivity limits of the surveys used in our analyses.

Table 1. Properties of Cool Evolved Stars

Type	Period Range	Z_0	σ_0	Reference
	(Days)	(pc)	(kpc^{-2})	
		a) Massive Stars		
M Supergiants	–	<100	1-2	1
		b) Chemically Peculiar Intermediate Mass Stars		
Carbon Stars	any	200	40	2
S-type Stars	any	200	12	3
		c) Oxygen-Rich Low- and Intermediate-Mass Variable Stars		
Mira	300–400	240	100	4
Semi-Regular	300–400	250	20	5
Mira	100–300	500-600	40–60	4
Semi-Regular	200–300	500	8	5
Semi-Regular	150–200	?		5
Semi-Regular	100–150	250	70	5
Semi-Regular	50-100	>190	130?	5
Irregular		300?	160?	5

References:

1. Jura and Kleinmann 1990a
2. Claussen *et al.* 1987
3. Jura 1988
4. Jura and Kleinmann 1992a
5. Jura and Kleinmann 1992b

The mid-infrared brightness of the types of stars listed in Table 1 is due not to the emission of their cool photospheres, but to the thermal re-emission of the starlight by dust in circumstellar dust clouds. The dust clouds are the result of the condensation of gas that outflows rapidly from these stars. Studies of the mid-infrared and far-infrared emission from these stars can be used to assess the amount of outflow from various types of stars, and therefore to determine which of those classes is predominantly responsible for replenishing the interstellar medium with material that has been processed in stellar interiors.

We have used two methods to evaluate the mass loss from these stars. One was to use the IRAS far-infrared data as a simple measure of the emission of cool dust far out in the atmospheres of these stars. If we make the assumption that all of the stars have spherically-symmetric, envelopes which are expanding at a constant velocity, then we can interpret the far-infrared brightnesses (combined with the luminosity of the sources, and an estimate of the outflow velocity) directly in terms of the mass loss rates. The result of applying this technique to the sources listed in Table 1, as well as extremely dusty sources which are not well represented in Table 1 (because most of them are Mira variables with periods longer than 400 days), is that, in the neighborhood of the Sun (d $<$ 1 kpc):

1. Carbon stars eject about as much material as oxygen-rich stars into the interstellar medium (Jura and Kleinmann 1990b), and
2. The total mass injection rate into the interstellar medium is dominated by a small number of stars, i.e., those few with mass loss rates $>10^5$ $M_\odot$/yr. (Jura and Kleinmann 1992b).

The second approach we used to evaluate the mass loss rates of evolves stars was a systematic study of the millimeter-wave spectral line emission of CO in the outer atmospheres of the 100 brightest stars belonging to classes represented in Table 1. The CO emission is a good measure of the outflow speed in the circumstellar envelopes, the total mass of outflowing material, and the geometry of the envelopes. We found (Margulis *et al.* 1990) that the emission of the carbon stars is consistent with spherically symmetric, optically thick, circumstellar envelopes. The oxygen-rich stars, in contrast, appear to have envelopes that are geometrically more complex. This result complicates the interpretation of far-infrared data, and calls for further observational studies at higher sensitivity and covering a larger sample, in order to develop a more realistic model.

The foregoing studies of sources that are bright in the near-infrared were motivated largely by the fact that there exists a rich database of information on the near-infrared luminosities of various classes of late type stars, and their exists a great deal of observational data for near-infrared-bright stars that helps to determine which of many classes of cool star should be assigned to a particular near-infrared source. Neither of these is true for the mid-infrared sources discovered by IRAS. We have carried out two preliminary observational studies designed to begin the process of determining how best to classify sources found in the IRAS survey. Its eventual goal is to determine whether the numbers and types of sources seen by IRAS are consistent with what's been seen in near-infrared surveys, or whether any new classes of sources are demanded by the IRAS results.

Our first effort was to obtain optical photometry of an objectively selected (flux-limited) sample of IRAS 12 μm sources with locations well above and below the plane of the Galaxy. It was expected that this region of the sky would have the least likelihood of containing previously undiscovered classes of infrared sources. The sample contains over 6000 stars, and we obtained optical photometry in the B (λ_{eff} = 0.44μm) and V ($\lambda_{eff} = 0.55\mu$m) bands for nearly 5000 of them.

Our crude analysis of these data shows that most of the IRAS 12 μm sources at high latitudes are cool oxygen-rich giants (cf. Figs. 1 and 2). The brightest high latitude mid-infrared sources are mass-losing giants like those seen in the *TMSS*, but only recently (with the completion of our analysis of Mira and Semi-Regular oxygen rich stars) could the analysis be attempted to determine whether the number of mass-losing giants is consistent with an extrapolation of results from the *TMSS*. This study is therefore continuing.

Besides the program of optical photometry, we have begun a program of near-infrared photometry of selected samples of IRAS sources near the galactic plane. We used near-infrared photometry to study these sources to minimize the effects of interstellar dust extinction which is greatest near the galactic plane. Four samples were studied: First, a flux-limited sample of 12 μm sources at high galactic latitudes were observed, to provide a consistency check with results deduced from optical photometry. Next, we observed two flux-limited samples of 12 μm sources in two different constellations of the galactic plane: Cygnus (near galactic longitude 90°), and Taurus (near longitude 180°). Finally, we observed a flux-limited sample of 12 μm sources that were found to be variable by the IRAS survey, since we suspected that these sources might be among the reddest stars found in the survey.

The colors of sources in these four samples (cf. Figure 3) are quite different. This shows that the population of stars in Cygnus and Taurus differ from each other and from sources seen at high latitudes. Also our observations of the variable stars confirmed our earlier expectation that these would be unusually red compared to sources in a flux-limited sample. These are the type of sources responsible for most of the mass return to the interstellar medium. This result was the observational basis for a recent theoretical analysis of IRAS results (Weinberg 1992) showing that IRAS detected a large (8 kpc diameter), massive, bar in the Milky Way. Further quantitative analysis of the results of our near-infrared photometry requires completion of the study of our high-latitude sample, and is therefore ongoing.

b) Galaxies

IRAS discovered that most galaxies like the Milky Way (spirals) are strong far-infrared emitters. This emission arises from dust internal to the galaxies which is heated by ambient starlight, as well as to dust in giant molecular clouds which are heated from within by newly-forming massive stars. A certain class of galaxies, however, have infrared spectral energy distributions that peak at such short wavelengths ($\lambda <= 60\mu$m) that all of their infrared emission must be due to molecular clouds or to emission from a non-stellar nucleus. We carried out a number of programs designed to study these "warm" *IRAS* galaxies.

Working collaboratively with R. R. Joyce (N.O.A.O.), and N. Z. Scoville (Caltech), M. Tamura and I have obtained long-slit infrared spectra in the region $2.0\mu\mathrm{m} \leq \lambda \leq 2.4\mu\mathrm{m}$ for NGC 1068 and M82 (Tamura *et al.* 1991). The first of these is the prototype of a class of galaxies known to have powerful compact (a.k.a. "active") nuclei. The second is the prototype of a class of galaxies whose far-infrared emission is attributed to a recent burst of formation of massive stars. The long-slit spectrometer permitted us to obtain spectra over a range of radial distances through the central regions of these galaxies. The purpose of the program was to test whether the enormous power emanating from the nucleus of NGC 1068 is due to a dense cluster of newly-formed massive stars, or to the emission of matter that surrounds and is falling rapidly into a massive black hole. If the former, then the spectrum of NGC 1068 should resemble the prototypical starburst galaxy, M82. If the latter, then we expected that the black hole would broaden the absorption features of stars in its vicinity, so that the spectrum of NGC 1068 would appear washed out by comparison to M82. Just such broadened absorption features were observed: the data are consistent with the presence of a 5 billion $M_{\odot}$ object within the central 240 pc. This is 5000 times the mass of the compact object thought to exist in our own galaxy. However, the detection of excited molecular hydrogen and ionized hydrogen within this region suggests that molecular clouds and massive stars are also present there.

We also continued a number of programs designed to survey the properties of larger groups of galaxies. In one program, we completed a near-infrared spectroscopic study (Campbell *et al.* 1990) of high-luminosity galaxies selected from the flux-limited sample of *IRAS* galaxies we studied previously (Smith *et al.* 1987). The goal of this work was to learn whether the most luminous IR galaxies commonly exhibit excited molecular hydrogen, which would indicate the presence of dense molecular clouds containing massive young stars. A positive detection would strongly support the hypothesis that their infrared emission was due to a recent burst of star formation. No new examples of galaxies with copious emission from molecular hydrogen were found, but the upper limits obtained on most galaxies in the sample were still consistent with a starburst scenario for their infrared luminosity.

In another program (Low *et al.* 1989), we obtained and analyzed photometry and spectroscopy of a group of quasars that were discovered by analyzing the *IRAS* survey. These quasars could be picked out of the survey because they had infrared colors which were cooler than normal stars but much warmer than normal galaxies—many of them emit peak energy at 60 μm. Over half of the quasars in our sample had not been found in earlier optical or radio surveys. These quasars were much redder than previously known quasars: it is now known that the range in ratio of infrared to optical luminosity for quasars spans 4 orders of magnitude, indicating that previous measures of the evolution of quasars that are based solely on optical surveys may be incomplete and biased. Besides their peculiar infrared colors, the *IRAS* quasars were also found to have peculiar optical spectra compared to the spectra of quasars found in optical surveys, which strengthens our conclusion that certain classes of quasars are systematically missed in optical surveys.

In the course of the previous investigation, it was discovered that there exists another class of objects—ordinary main sequence stars not unlike the Sun—some of which exhibit enormous far-infrared excesses. This phenomenon was first discovered in the study of the *IRAS* observations of the bright star Vega. We found additional examples of this phenomenon where the amount of stellar luminosity that was emerging in the infrared was 10,000 times greater than that of Vega! The star with the most dramatic excess (20 % of its energy emerges in the far-infrared) is a K5 dwarf visual double star. Additional studies have shown that this source is actually a triple system, since the absorption lines vary in velocity with a period of only a few months. No consistent picture that explains the infrared and dynamical properties of this system has yet been developed. Meanwhile, studies are continuing to find additional examples of main-sequence stars with large far-infrared excesses, since the presence of binarity among such stars may give a clue to the peculiar properties of the peculiar K5 dwarf already found.

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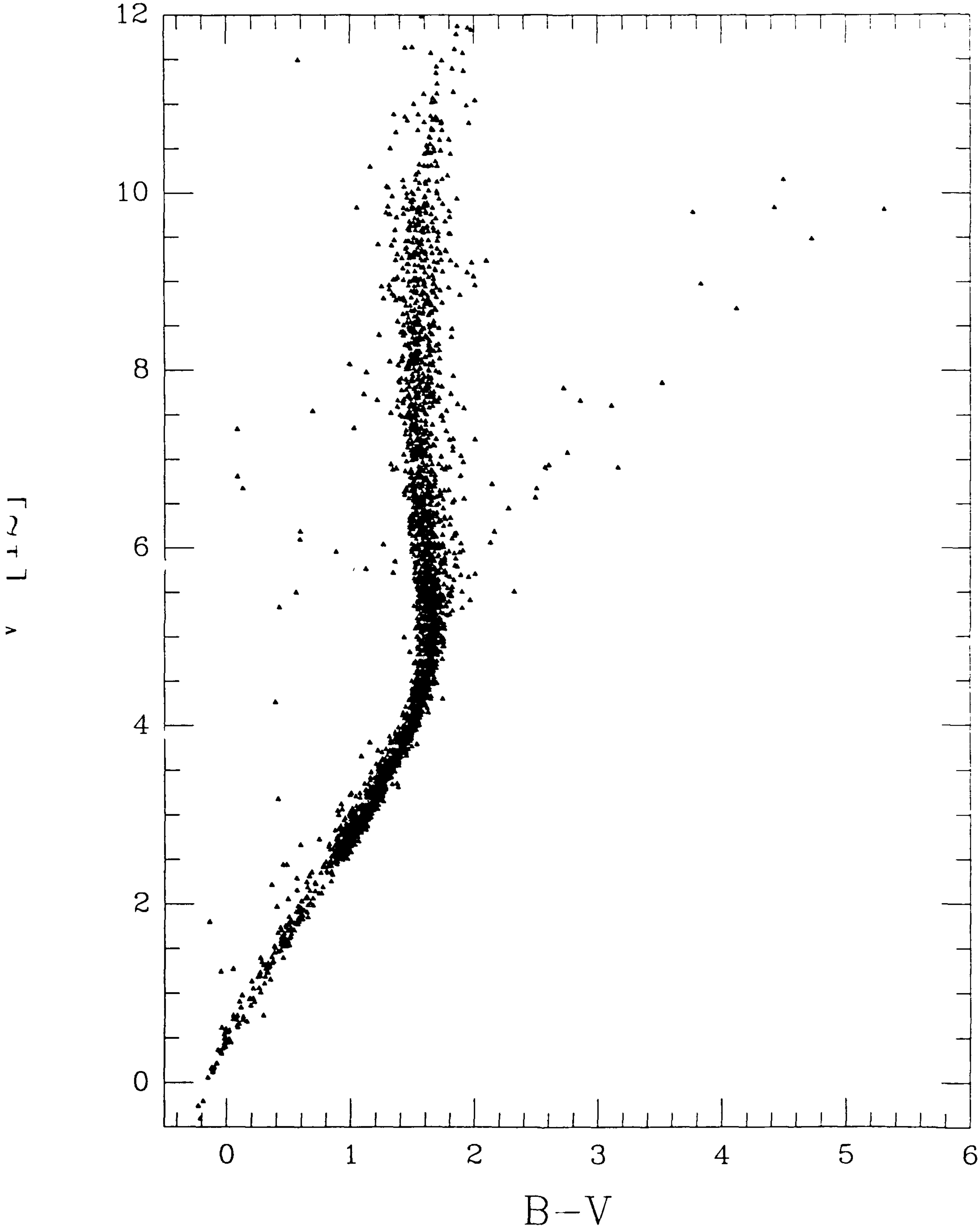

FIGURE 1

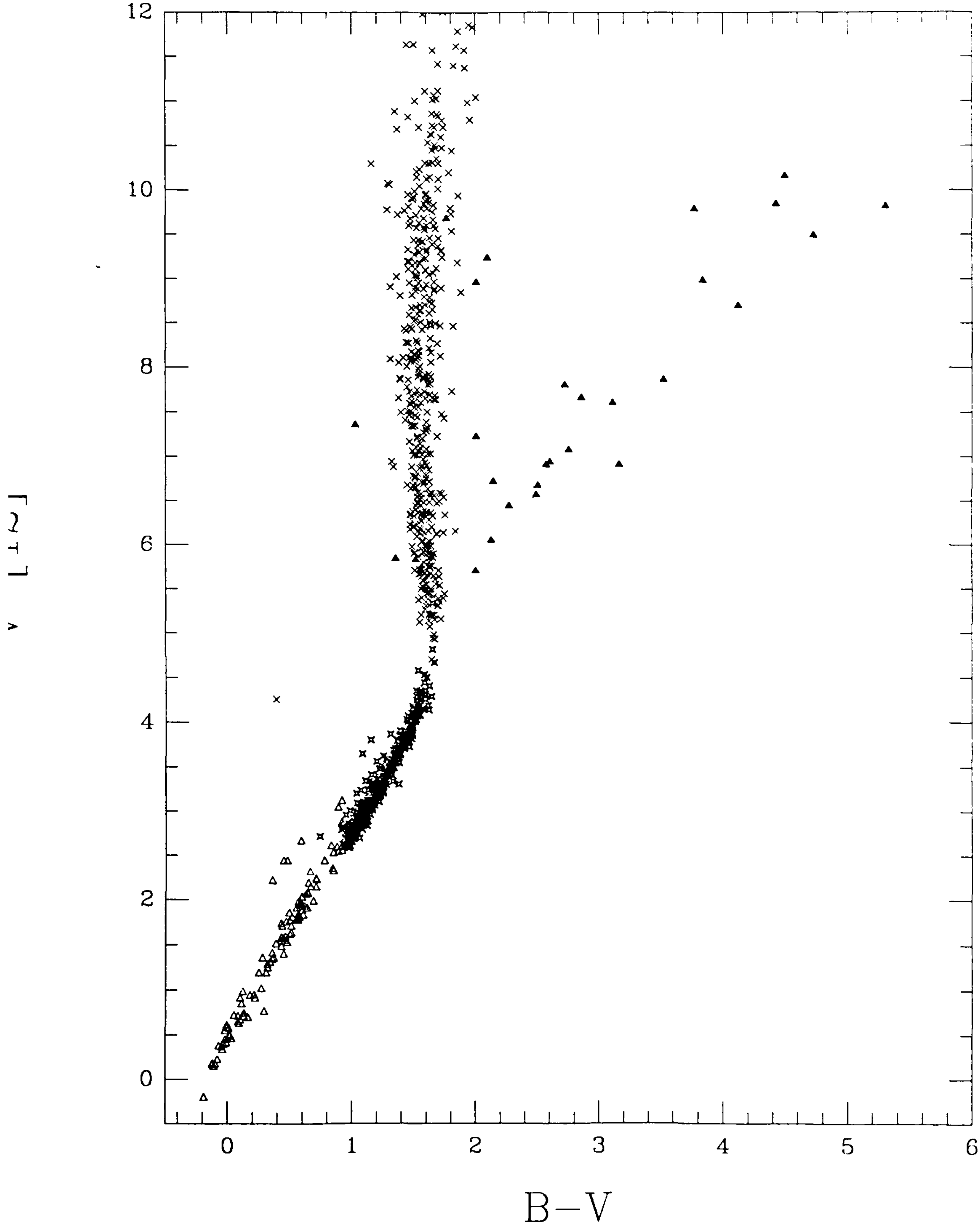

FIGURE 2

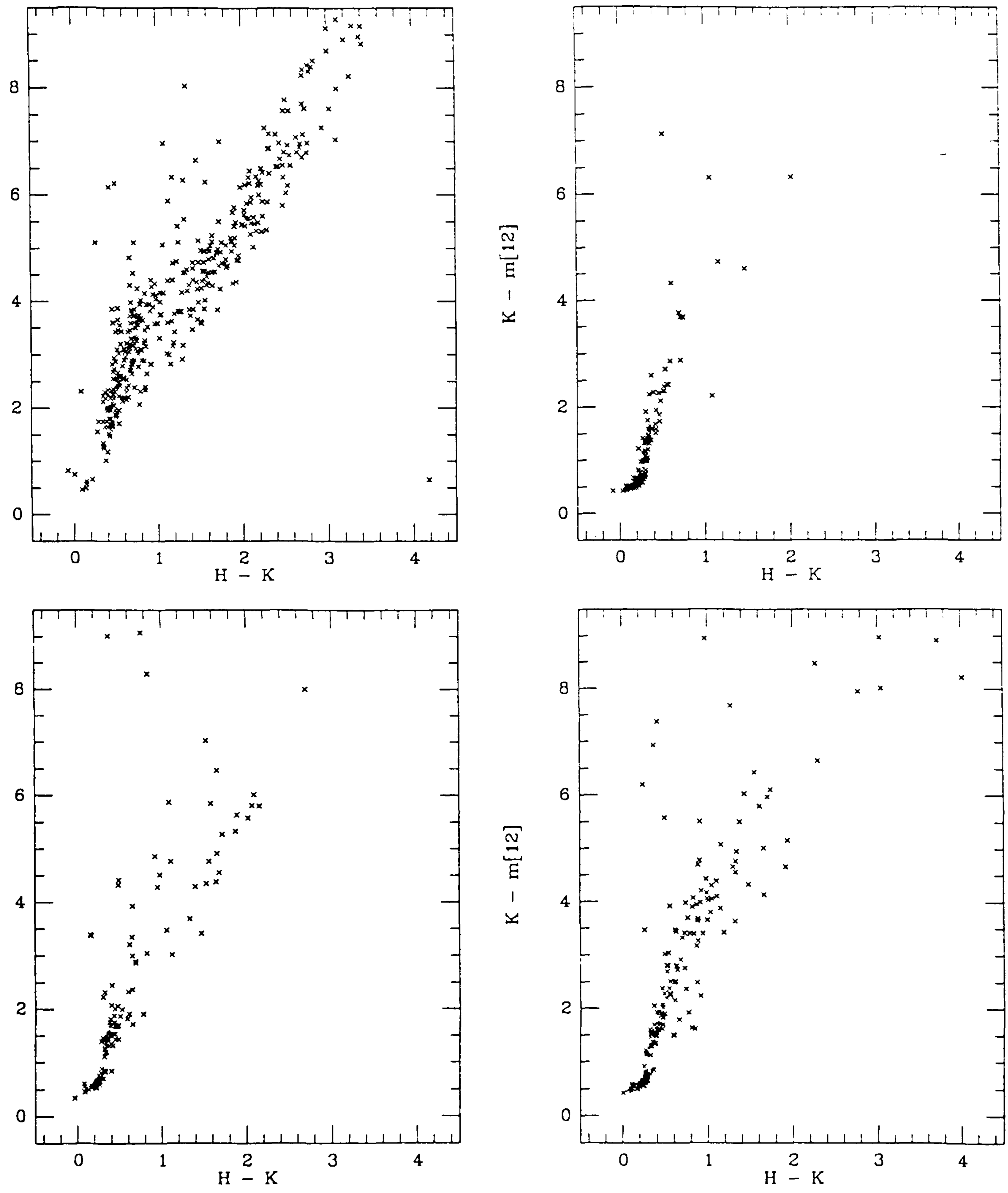

FIGURE 3

Figure Captions

Figure 1. Two-color plot of nearly 5000 sources brighter than 1 Jy at 12 μm and located in one of two cones (galactic latitude $> 30°$ and galactic latitude $< -30°$). Each "color" is the difference in the apparent magnitude of a source at two wavelengths. B, V, and [12] refer to the magnitudes at effective wavelengths of 0.44, 0.55, and 12 μm respectively. Thus, the abscissa is a logarithmic measure of the flux densities at 0.44 and 0.55 μm, while the ordinate is a logarithmic measure of the flux densities at 0.55 and 12 μm. Stars with temperatures of 10,000K should have $B - V = 0$ mag., and $V-[12] = 0$ mag.; however, the broad-band *IRAS* data have not been color-corrected, which effectively shifts the data upward by $\Delta(V - [12]) = 0.4 mag.$. Cooler stars (i.e., those with redder colors) are located to the left and upward in the diagram.

Figure 2. Two-color plot of those sources shown in Figure 1 for which spectral classifications are available. This figure define the limits of the ranges of colors for stars in different classes. The axes are the same as in Figure 1. The open triangles are main-sequence (i.e., hydrogen-burning) stars like the Sun. All of the other sources on the plot are evolved stars of different types. The star symbols designate known K giants (stars which have just evolved past the hydrogen burning phase and have temperatures near 4000 K). The crosses designate M giants (cooler, more evolved stars). The filled triangles represent carbon stars (stars which have evolved to the point that newly-formed carbon has been dredged up from their interiors). The very red colors of most of the M giants and carbon stars are due thermal re-radiation of starlight by circumstellar dust.

Figure 3. Two-color plots of sources in each of four samples (see p. 6). The axes are analogous but not equal to those shown in Figures 1 and 2. The abscissa refers to the color measured between two bands centered at effective wavelengths of 1.65 μm (H band) and 2.2 μm (K band), while the ordinate refers to the color measured between the K band and the *IRAS* 12 μm band.

Top left:	the sample of *IRAS* variables
Top right:	*IRAS* high latitude sources
Bottom left:	*IRAS* sources in Taurus
Bottom right:	*IRAS* sources in Cygnus

II. Publications

1. "The Spatial, Temporal, and Photometric Properties of AGB Stars". Kleinmann, S. G. 1989, in *Evolution of Peculiar Red Giant Stars*, I. A. U. Colloquium No. 106, ed. H. R. Johnson and B. Zuckerman (Cambridge: Cambridge University Press), p. 13.
2. "The Properties of Infrared Color-Selected Quasars", Low, F. J., Cutri, R. M., Kleinmann, S. G., and Huchra, J. P. 1989, *Astrophysical Journal (Letters)*, **340**, L1.
3. "Dust-Enshrouded Asymptotic Giant Branch Stars in the Solar Neighborhood", Jura, M., and Kleinmann, S. G., 1989, *Astrophysical Journal*, **341**, 359.
4. "High Luminosity Carbon Stars in the Galactic Anticenter". Jura, M., Joyce, R. R. and Kleinmann, S. G. 1989, *Astrophysical Journal*, **336**, 924.
5. "The Probable Dust Formation Episode Around ρ Cas", Jura, M., and Kleinmann, S. G. 1990, *Astrophysical Journal*, **351**, 583.
6. "Mass-Losing M Supergiants in the Solar Neighborhood", Jura, M., and Kleinmann, S. G. 1990, *Astrophysical Journal Supplement Series*, **73**, 769.
7. "^{12}CO Emission in the Envelopes of Cool Stars in the Solar Neighborhood", Margulis, M., VanBlerkom, D. J., Snell, R. L., and Kleinmann, S. G. 1990, *Astrophysical Journal*, **361**, 673.
8. "Very Dusty Carbon-Rich Asymptotic Giant Branch Stars between ~1 and ~ 2.5 Kiloparsecs From the Sun". 1990, *Astrophysical Journal*, **364**, 663.
9. "Near Infrared Long Slit Spectra of NGC 1068", Tamura, M., Kleinmann, S. G., Scoville, N. Z., and Joyce, R. R. 1991, *Astrophysical Journal*, **371**, 131.
10. "A Search for Shocked Hydrogen in High-Luminosity Galaxies", Willner, S. P., Campbell, A., Huchra, J. P., and Kleinmann, S. G. 1991, *Astronomical Journal*, **100**, 635.

IV. Participating Professionals[a]

Principal Investigator:	Susan G. Kleinmann, Professor
Co-Investigator:	David J. VanBlerkom, Professor
Post-Doctoral Research Associate:	Motohide Tamura, Research Associate
Graduate Research Associate:	Lori Allen

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[a] All members of the Department of Physics and Astronomy, University of Massachusetts, Amherst, MA.

IV. Interactions

1. M. I. T. Astrophysics Colloquium, September 27, 1989. Subject: "The Space Distribution of AGB Stars".
2. Center for Astrophysics Optical-Infrared Astronomy Lunch Talk, October 12, 1989. Subject: "The New Two Micron Sky Survey."
3. Boston University Astronomy Colloquium, November 29, 1989. Subject: "Powerful Galaxies".
4. UCLA *Astronomy Colloquium*, April 10, 1990. Subject: "Warm IRAS Sources".

IV. New Discoveries, Inventions, Patent Disclosures

None